

Implementing wildlife fences along highways at the appropriate spatial scale: A case study of reducing road mortality of Florida Key deer

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Abstract

Florida Key deer mortality data (1966–2017) showed that about 75% of all reported deer mortalities were related to collisions with vehicles. In 2001–2002, the eastern section of US Hwy 1 on Big Pine Key (Florida, USA) was mitigated with a wildlife fence, 2 underpasses, and 4 deer guards. After mitigation, the number of reported Key deer road mortalities reduced substantially in the mitigated section, but this was negated by an increase in collisions along the unmitigated section of US Hwy 1 on Big Pine Key, both in absolute numbers and expressed as a percentage of the total deer population size. The data also showed that the increase in Key deer collisions along the unmitigated highway section on the island could not be explained through an increase in Key deer population size, or by a potential increase in traffic volume. The overall Key deer road mortality along US Hwy 1 was not reduced but was moved from the mitigated section to the nearby unmitigated section. Thus, there was no net benefit of the fence in reducing collisions. After mitigation, a significant hotspot of Key deer-vehicle collisions appeared at the western fence-end, and additional hotspots occurred further west along the unmitigated highway. Exploratory spatial analyses led us to reject the unmitigated highway section on Big Pine Key as a suitable control for a Before-After-Control-Impact (BACI) analysis into the effectiveness of the mitigation measures in reducing deer-vehicle collisions. Instead, we selected highway sections west and east of Big Pine Key as a control. The BACI analysis showed that the wildlife fence and associated mitigation measures were highly effective (95%) in reducing deer-vehicle collisions along the mitigated highway section. Nonetheless, in order to reduce the overall number of deer-vehicle collisions along US Hwy 1, the entire highway section on Big Pine Key

would need to be mitigated. However, further mitigation is complicated because of the many buildings and access roads for businesses and residences. This case study illustrates that while fences and associated measures can be very effective in reducing collisions, wildlife fences that are too short may result in an increase in collisions in nearby unmitigated road sections, especially near fence-ends. Therefore it is important to carefully consider the appropriate spatial scale over which highway mitigation measures are implemented and evaluated.

Keywords

Collisions, fences, fence-end, key deer, mitigation, net benefit, road ecology, roadkill

Introduction

Most wildlife mitigation measures along highways are aimed at improving human safety, reducing direct wildlife mortality, and providing safe crossing opportunities for wildlife (e.g. Ford et al. 2009; van der Grift et al. 2017). Fences that are designed for large mammals, that are carefully installed and maintained, and that are implemented over at least several miles of road length, can reliably reduce collisions by at least 80% (Huijser et al. 2016a; Rytwinski et al. 2016). Since fences alone would result in a near absolute linear barrier for the target species, fences are often combined with wildlife crossing structures under or over the road. These underpasses and overpasses allow wildlife to safely cross to the other side of the road, and, in general, their use increases when they are connected to wildlife fences that help guide the animals towards the structures (Dodd et al. 2007; Gagnon et al. 2010). The suitability of the different types of crossing structures (e.g. underpasses vs. overpasses) and their dimensions (height, width, length), depend on the species (e.g. Sawyer et al. 2016), and sometimes also the sex and age of the individuals (e.g. Ford et al. 2017). Nonetheless, use of wildlife crossing structures can be considered substantial and can increase over time, presumably because the animals learn about the location of the structures and that they are safe to use (Clevenger and Barrueto 2014; Huijser et al. 2016b).

While a combination of fences and crossing structures is probably the most reliable and robust measure to improve human safety, reduce direct wildlife mortality, and provide safe crossing opportunities for wildlife, there is still much to learn on how to both make fences and crossing structures more effective and have the structures more readily accepted by different species (e.g. Huijser et al. 2015a; Rytwinski et al. 2016; Denneboom et al. 2021). One of the factors that affects the effectiveness of wildlife fences in reducing collisions is the scale at which the fence is implemented. For large mammals, at least 5 kilometers (3 miles) of road length needs to be fenced to reliably reduce collisions by 80% or more (Huijser et al. 2016a). Collisions that still occur within the fenced road sections tend to be concentrated near the fence-ends (Huijser et al. 2016b; Plante et al. 2019). Embedding barriers (e.g. wildlife guards or electrified barriers) in the travel lanes at fence-ends, can reduce intrusions into the fenced

road corridor (Peterson et al. 2003; Gagnon et al. 2010). However, collisions can also be concentrated just beyond the fence-ends in the adjacent unmitigated road sections (Huijser et al. 2016b). On a larger spatial scale, there are also some cases where collisions may have been moved further into the adjacent unmitigated road sections (van der Grift and Seiler 2016) and where there is no evidence that there was a net benefit of wildlife fences. Therefore, it is important to install fences of sufficient length and to choose the locations for fence-ends carefully. Fenced road sections should include a buffer zone that extends well beyond the known hotspots for wildlife-vehicle collisions (Huijser et al. 2015a). Additional considerations such as habitat and topography can also help identify suitable locations for fence-ends.

Here we investigate the effectiveness of a wildlife fence and associated measures in reducing collisions with an endangered species, the Florida Key deer (*Odocoileus virginianus clavium*), on Big Pine Key, Florida, USA. We first explored the absolute Key deer road mortality numbers over the years and evaluated the spatial pattern in reported collisions with Key deer before and after the fence was constructed. Then we corrected the number of reported collisions for the Key deer population size for both the mitigated highway section and different potential control road sections for a Before-After-Control-Impact (BACI) analysis through which we evaluated the effectiveness of the fence. We also investigated potential differences in traffic volume between the mitigated and unmitigated highway section on Big Pine Key, and how traffic volume may have affected Key deer collisions along the unmitigated highway section. These exploratory analyses allowed us to find a suitable control for the BACI analysis. The careful consideration of different potential control road sections also allowed us to explore the net benefit of the wildlife fence on a larger spatial scale. The results help us to be more effective when designing wildlife mitigation measures along highways and to be more accurate when evaluating their effectiveness.

Methods

Study area and mitigation measures

In 1957, the National Key Deer Refuge was established in the Lower Florida Keys, Florida, USA. It is one of four national wildlife refuges in the area. The refuges were established to protect the endangered Key deer along with other endangered species and the habitat they depend on. At the time, hunting had reduced the Key deer population to fewer than 50 individuals (Hardin et al. 1984). Since then, the Key deer population has increased to an estimated 1,050 individuals in 2017 (U.S. Fish and Wildlife Service 2019). Most of the deer are found from Sugarloaf Key (west) to Big Pine Key and No Name Key (east), partially aided by reintroduction on some islands (Parker et al. 2008). An estimated 85% of the Key deer occur on Big Pine Key and No Name Key (U.S. Fish and Wildlife Service 2019). Parts of the islands have been urbanized, resulting in a mosaic of natural habitat (pine rocklands, freshwater marshes, tropical hard-

wood hammocks, transitional buttonwood mangroves, mixed mangrove forests, and beach berm communities), residential areas, and commercial lots. This development has especially occurred on Big Pine Key. Additionally, tourism has increased substantially over the last several decades (peak season November–April) (Rockport Analytics 2019; Braden et al. 2020; Key West Travel Guide 2021). This has resulted in more than five million visitors per year to the Florida Keys (Rockport Analytics 2019), many of whom travel on US Hwy 1 from the mainland of peninsular Florida towards Key West. The Average Annual Daily Traffic (AADT) for US Hwy 1 on Big Pine Key was about 18,000 vehicles in 2016 (Consulting KBP Inc. 2017). Since there are no natural predators for key deer, conflicts with humans, including vehicle collisions, are now the most important causes of mortality for the deer (U.S. Fish and Wildlife Service 2019). Since 1966, wildlife refuge staff and Florida Fish and Wildlife Conservation Commission law enforcement staff, aided by other law enforcement staff and the public, have recorded Key deer mortalities, including road mortality. Although there is no standardized monitoring effort for Key deer struck by vehicles, there is high reporting effort because of their endangered status and because of the public concern about the species. The historic road mortality data showed that most direct road mortality occurred along US Hwy 1 on Big Pine Key (Parker 2006), especially in the early morning and early evening (Braden et al. 2020). Note that not every dead Key deer and cause of death is reported and recorded in the database. This means that there are inherent biases in the data; for example, a roadkilled Key deer is more likely to be found and recorded than a drowned Key deer.

In 2001–2002 a 1.64 mi (2.64 km) section of US Hwy 1 on the east side of Big Pine Key was mitigated with a 2.4 m (8 ft) high fence, 2 underpasses, and 4 deer guards (similar to cattle guards) (Braden et al. 2008; Parker et al. 2011) (Fig. 1). US Hwy 1 on the west side of the island was left unmitigated because of the access to businesses and residential areas (Parker et al. 2008). The mitigated highway section is largely situated within natural habitat with only a few access points for side roads. The western fence-end and the three side roads all have a deer guard embedded in the travel lanes. The eastern fence-end end at the Spanish Harbor Channel Bridge does not have a deer guard. Based on a Before–After comparison in a previous study, the mitigation measures along US Hwy 1 reduced Key deer collisions by about 90% in the mitigated road section (Parker et al. 2011). Furthermore, Key deer use the two underpasses, and the use has been increasing with the age of the structures (Braden et al. 2008; Parker et al. 2011). However, Key deer collisions continued to increase overall, i.e. on other unmitigated road sections (Parker et al. 2011). The continued increase in Key deer–vehicle collisions was attributed to the growing Key deer population size and traffic volume, especially on Big Pine Key and US Hwy 1 (Parker et al. 2011). While hurricane Irma blew over large sections of the wildlife fence along US Hwy 1 in September 2017, this did not affect our study as we only included Key deer mortality data through 2016 for our evaluation of the effectiveness on the measures in reducing collisions (see later). Other mitigation measures aiming at reducing collisions with Key deer along both the mitigated and unmitigated section of US Hwy 1 on Big Pine Key include low maximum posted speed limits (daytime 45 MPH;



Figure 1. The mitigated section of US Hwy 1 on Big Pine Key.

nighttime 35 MPH), mobile speed radar units informing drivers of the speed of their vehicle, parked police cars (no law enforcement personnel present), and a variety of warning and informational signs.

Key deer road mortality numbers and spatial patterns

We used the existing database on Key deer mortalities between 1966 (first record 9 March 1966) through partway 2017 (last record 9 November 2017) to assess road mortalities versus mortality from other causes. We calculated the absolute number of Key deer road mortalities along all roads combined (1966–2016) and in the ten years before mitigation (1991–2000) and in the fourteen years after mitigation (2003–2016) along both the mitigated and unmitigated highway section on Big Pine Key. We also explored where Key deer collisions occurred before and after the mitigation measures were implemented. Exploration of the spatial pattern of Key deer road mortalities after the mitigation measures were implemented allowed us to identify locations where further efforts to reduce Key deer-vehicle collisions should be directed, should one choose to do so. In addition, the spatial patterns in Key deer collisions before and after the mitigation measures were implemented provided the first step in identifying a suitable control for a BACI analysis to calculate the effectiveness of the fence and associated measures.

We investigated where the highest greatest concentrations of Key deer roadkill were after the eastern section of US Hwy 1 was mitigated. For this hotspot analysis, we only selected roadkill records of Key deer for the most recent 10-year period (2007 through 2016, $n=1,182$), regardless of where they occurred i.e. both on and off Big Pine Key, both inside and outside the mitigated section of US Hwy 1. We chose to use this subset of records as a balance between having recent data that identify current hotspots, and having a robust sample size. To identify hotspots, we conducted a Kernel density analysis using ArcGIS 10.6.1 (ESRI 2018a) for point features of Key deer-vehicle collision locations using a 25 m cell size (82 ft \times 82 ft). A 25 m cell size is relatively fine scale but still accommodates for some spatial inaccuracies in GPS coordinates. The Kernel density analysis calculates the density of roadkills in a neighborhood around each cell and is based on the quartic kernel function described by Silverman (1986). Consistent with Gomes et al. (2009) we set the neighborhood search radius at 500 m (0.31 mi). On a straight road this means that Key deer roadkill that are up to about 500 m away are included in the density analysis for each cell. To help interpret the results of the Kernel density analyses and identify hotspots, we displayed the raster output using a heat map classification with varying densities of Key deer collisions. We used percentage breaks to create five categories (<5%, 5–<25%, 25–<50%, 50–<75%, and 75–100%) that display the areas with the highest densities of Key deer collisions (<5%) to areas with the lowest densities (75–100%).

Wherever a fence ends, there is a possibility of a concentration of collisions just beyond the fence end; the “fence-end effect”. For example, after implementation of the fence, some Key deer may have walked alongside the fence until they reached one of the two fence-ends. They could then cross the highway at-grade at the fence-end where they are exposed to potential collisions with vehicles. If such fence-end effects are indeed present, and if such road sections would be included in the control, it would result in an overestimation of the collisions in the control section and, through the BACI analysis, it would then also overestimate the effectiveness of the mitigated road section. Therefore, for a control to be suitable, it should not be influenced by the mitigation measures, and potential fence-end effects should be excluded from the control. We explored the potential presence of a concentration of Key deer road mortality near the western and the eastern fence-ends through an optimal hot spot analysis (Getis-Ord G_i^*) in ArcGIS 10.6.1 (ESRI 2018b). This analysis identifies statistically significant spatial clusters of hotspots and cold spots of Key deer road mortalities. We selected Key deer road mortality observations along US Hwy 1 on Big Pine Key, both along the mitigated and unmitigated road section, before and after mitigation, up to 50 m from the highway. We then created a bounding polygon around the highway (50 m buffer from approximately the center of the highway) to allow for some spatial imprecision in the original data. We conducted separate analyses for the “before” (1991–2000; 331 observations, 5 outliers) and “after” data (2003–2016; 795 observations, 11 outliers). Within the optimal hot spot analysis (Getis-Ord G_i^*) procedure, an outlier is defined as a location that is more than a three standard deviation distance

away from its closest noncoincident neighbor. For the “before” data, the optimal grid size was 43 m, and the optimal fixed distance band was 302 m. For the “after” data, the optimal grid size was 44 m, and the optimal fixed distance band was 164 m.

Key deer road mortality in relation to population size

We investigated the net benefit of the mitigation measures by calculating Key deer road mortality as a percentage of the Key deer population size for all roads combined, US Hwy 1 on Big Pine Key (mitigated and unmitigated sections combined), and the mitigated road section of US Hwy 1 on Big Pine Key. We conducted the same analysis for different sections of unmitigated road sections of US Hwy 1 to identify a suitable control for the BACI analysis. The potential control sections that were evaluated included the unmitigated road section of US Hwy 1 on Big Pine Key up to the fence-end, the unmitigated road section of US Hwy 1 on Big Pine Key excluding a potential fence-end effect (see previous section), and the unmitigated road sections of US Hwy 1 west and east of Big Pine Key. This allowed for a second step in finding a suitable control for the BACI analysis as the analyses described above can detect evenly distributed increases in road mortality in different potential control road sections that are associated with the implementation of the mitigation measures.

To express Key deer road mortality as a percentage of the Key deer population size, we relied on historical population estimates. Unfortunately, total Key deer population size estimates were only available for certain years (Appendix 1). The respective authors usually presented both a minimum and maximum population estimate. Therefore, we calculated the average population size for each of the available minimum and maximum population estimates. We then fitted an exponential growth curve through the available population size estimates, allowing us to calculate the associated population size estimate for each calendar year before (1991 through 2000) and after mitigation (2003 through 2014). Note that we did not calculate population estimates after 2014, the last year the population was estimated based on field work, as we did not want to extrapolate beyond the data collection period. We tested for potential differences between the percentage of roadkilled Key deer of the total population size in the years before and after the mitigation measures were implemented (Kruskal-Wallis One-Way ANOVA on Ranks).

Traffic volume

To investigate if traffic volume may have played a role in the increase in Key deer road mortality along the unmitigated section of US Hwy 1 on Big Pine Key after the mitigation measures were implemented, we summarized traffic volume on US Hwy 1 on Big Pine Key between 1994–2017 based on traffic counter data (URS 2017; FDOT 2018). We tested for a potential difference in traffic volume before (1994–2000) and after (2003–2017) implementation of the fence and associated mitigation measures (two-sided t-test).

Effectiveness of the mitigation measures

We investigated the effectiveness of the mitigation measures in reducing collisions with Key deer through a BACI analysis. We selected roadkill records of Key deer; 10 years before the implementation of the mitigation measures (1991 through 2000), and 14 years after the implementation of the mitigation measures (2003 through 2016). We searched for a suitable control section of US Hwy 1 through the analyses described in the sections above. The unmitigated section of US Hwy 1 on Big Pine Key, starting immediately adjacent to the fence-end, was not suitable due to a concentration of collisions just beyond the fence-end. Excluding the fence-end effect still did not result in a suitable control as Key deer road mortality expressed as a percentage of the Key deer population size was still elevated, presumably because of the nearby mitigated road section. However, the combined unmitigated road sections US Hwy 1 west (11.7 mi; 18.8 km) and east (2.7 mi; 4.3 km) of Big Pine Key seemed unaffected by the implementation of the mitigation measures on Big Pine Key. Therefore, we selected these road sections as the control for the BACI analysis (total length for the control was 14.4 mi; 23.2 km) (Fig. 2). Since there was some spatial imprecision in the original data, we included observations of roadkilled Key deer that were up to 50 m from either side

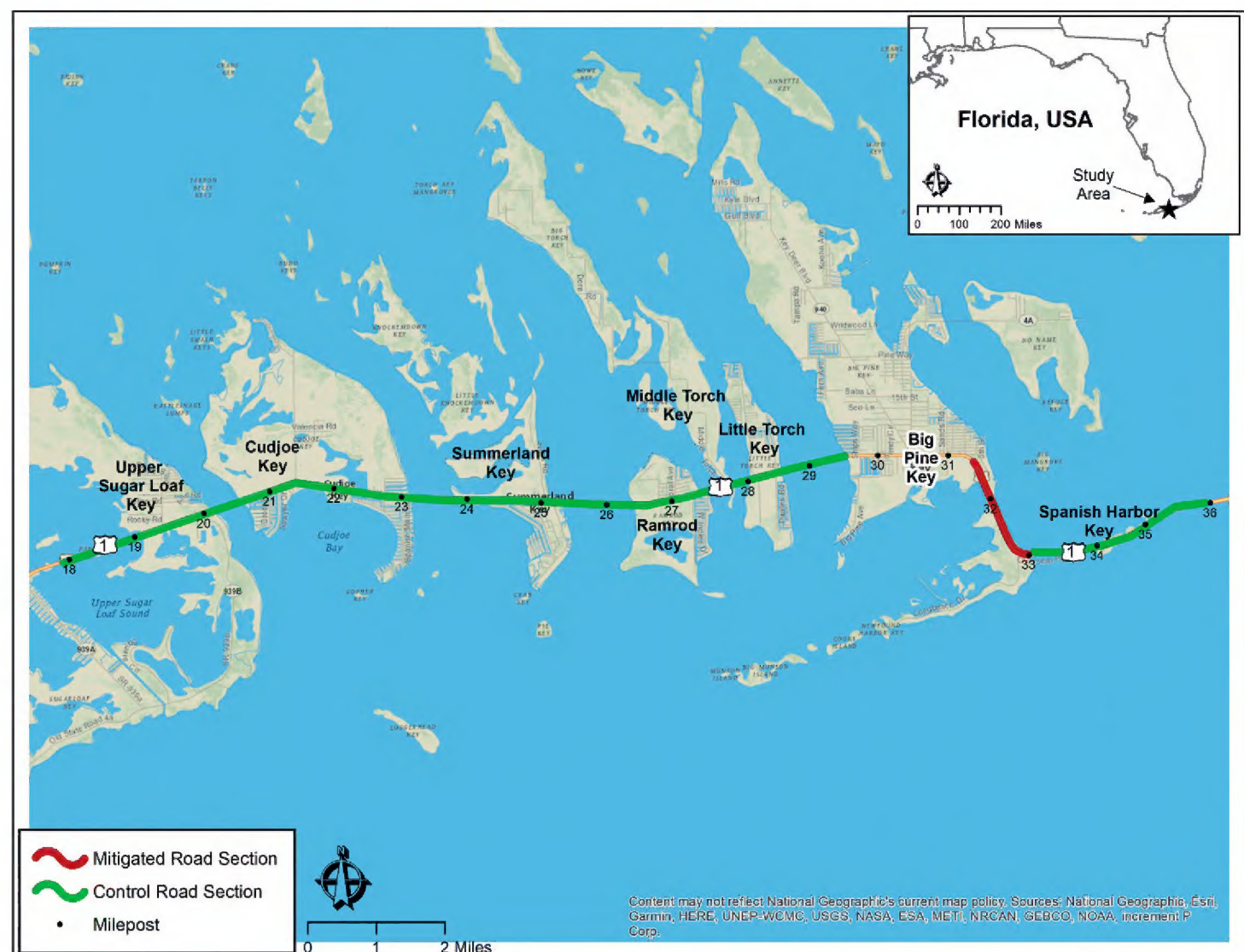


Figure 2. The mitigated section of US Hwy 1 on Big Pine Key and the two highway sections west and east of Big Pine Key that served as the control in the BACI analysis.

of US Hwy 1. For the BACI analysis, we calculated the number of Key deer roadkill records per mile for each calendar year for the control (unmitigated) and the impact (mitigated) road section. We calculated the BACI effect based on the mean number of roadkilled Key deer per mile per year (μ) in the impact road section and the control road section before and after the measures were implemented according to $(\mu_{\text{control,after}} - \mu_{\text{control,before}}) - (\mu_{\text{impact,after}} - \mu_{\text{impact,before}})$. In addition, the Key deer roadkills per mile per year were transformed ($\ln(x+0.1)$) to make the count variable resemble a normal distribution. This allowed for the investigation of a potential interaction of the before-after and control-impact parameters through an ANOVA. Should there be an effect of the treatment (i.e. the wildlife fence and the associated mitigation measures), we expected the effect to result in fewer collisions rather than more. Hence our ANOVA was a one-sided test.

Results

Key deer road mortality numbers and spatial patterns

There were 4,753 recorded mortalities of Key deer from 1966–2017. Overall, roadkill was the most common recorded cause of mortality ($N=3,412$, 71.8%), followed by “undetermined” ($N=681$, 14.3%), and disease ($N=276$, 5.8%). Drowning, predation by dogs, entanglement, intraspecies combat, poaching, humans (various causes), and physical impact of hurricanes each represented less than 5% of the recorded mortalities. Road mortality has consistently been the leading known cause of mortality since record keeping began in 1966. The average percentage of Key deer road mortalities out of all recorded Key deer mortalities for each year (1966–2016) per year was 75.5% (SD=10.2). While the absolute number of recorded Key deer road mortalities dropped substantially in the mitigated road section after the mitigation measures were implemented in 2001–2002, the number of Key deer road mortalities for all roads combined and for the unmitigated section of US Hwy 1 on Big Pine Key continued to increase (Fig. 3).

After the mitigation measures were implemented, Key deer road mortality was concentrated along the unmitigated western section of US Hwy 1 on Big Pine Key (Fig. 4). There were two main hotspots; one on the west side of Big Pine Key (opposite of the canals (W. Cahill Ct.) until Deer Run Tr.), and one at the west end of the wildlife fence (opposite of the St. Peter Catholic Church), extending further west till Cunningham Ln. Post-mitigation, there were 575 reported Key deer road mortalities in the unmitigated section of US Hwy 1, and 25 in the fenced section.

Before the eastern section of US Hwy 1 was mitigated, there was a significant concentration of Key deer-vehicle collisions at the eastern edge of Big Pine Key (Fig. 5a). This hotspot disappeared after the implementation of the mitigation measures, and almost the entire length of the mitigated road section turned into a significant cold spot (Fig. 5b). However, after mitigation, a significant hotspot appeared at the western fence-end, extending for about 300 m (984 ft) into the unmitigated high-

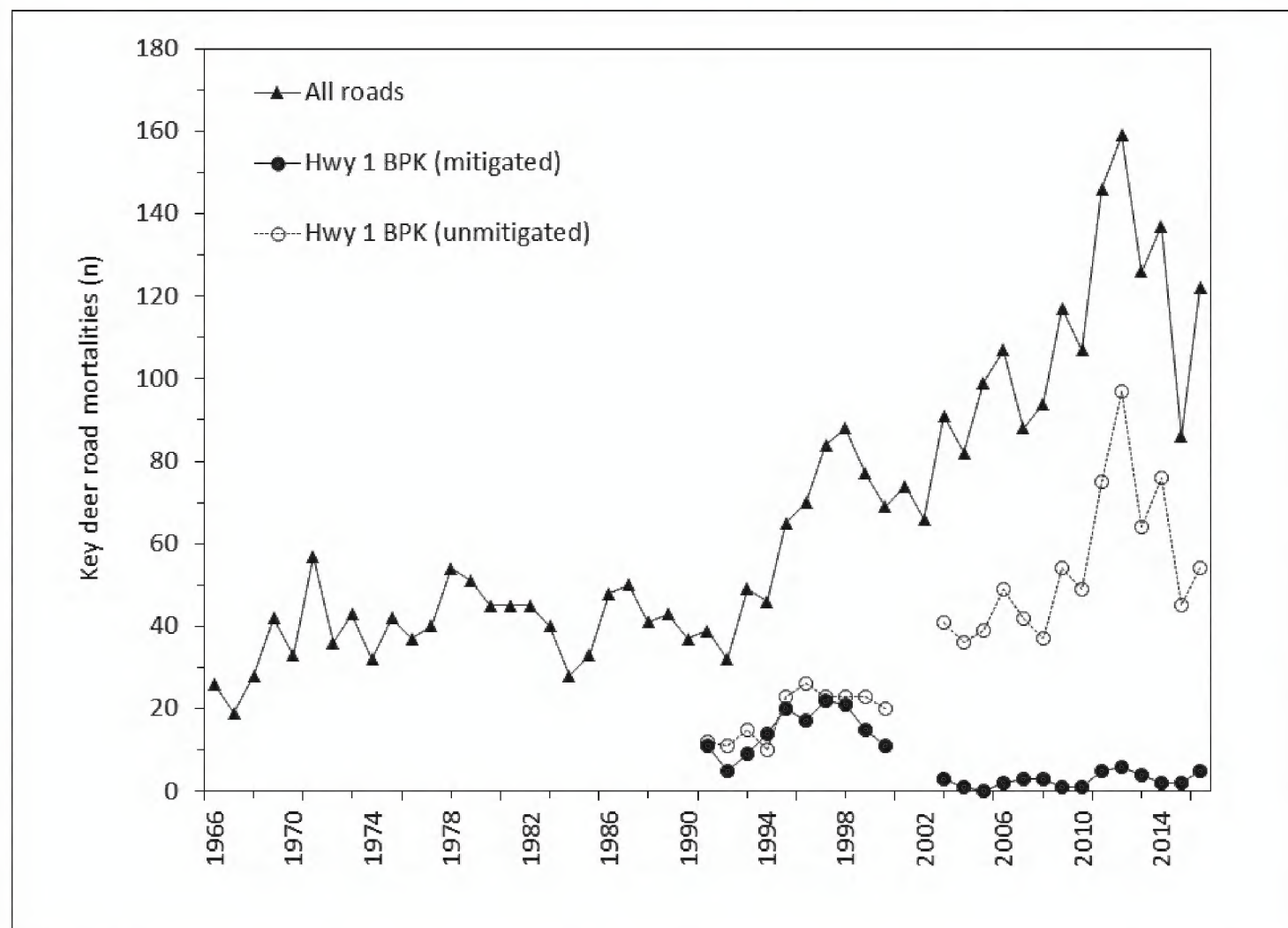


Figure 3. The number of Key deer road mortalities per year along all roads combined (1966–2016) and during the ten years before (1991–2000) and the fourteen years after mitigation (2003–2016) along both the mitigated and unmitigated section of US Hwy 1 on Big Pine Key (BPK).

way section (Fig. 5b). Other significant hotspots were present further west along the unmitigated section of US Hwy 1. The 90% confidence hotspot extended about 325 m (1,066 ft) from the western fence-end (142 records from 2003–2016; 18.7% of the Key deer road mortalities on the unmitigated highway section on Big Pine Key). There were 617 records (81.3%) outside this hotspot along the unmitigated highway section on Big Pine Key. The 95% confidence hotspot (119 records from 2003–2016; 15.7% of the Key deer road mortalities on the unmitigated highway section on Big Pine Key) extended about 280 meters (919 ft) from the western fence-end. There were 640 records (84.3%) outside this hotspot along the unmitigated highway section on Big Pine Key.

Key deer road mortality in relation to population size

Key deer population size has grown exponentially since the 1940s (Fig. 6). While there were only seven population size estimates available in total, the population may have been stable or experienced a slight decline between 1974 and 1990. Nonetheless, in general, and specifically since the mitigation measures were implemented in 2001–2002, the population size has grown exponentially.

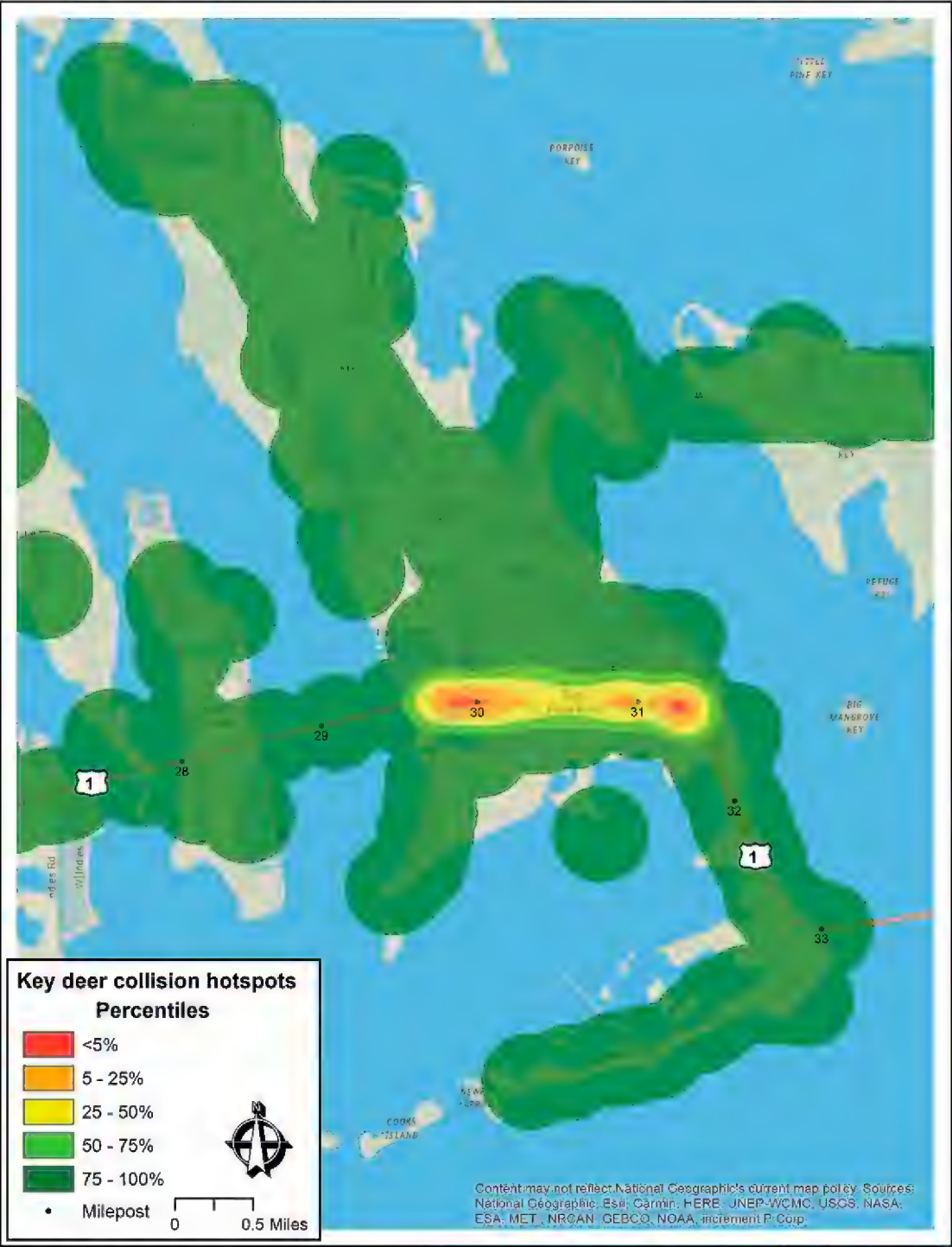


Figure 4. Kernel density hotspot map using percentiles for Key deer-vehicle collisions (2007–2016).

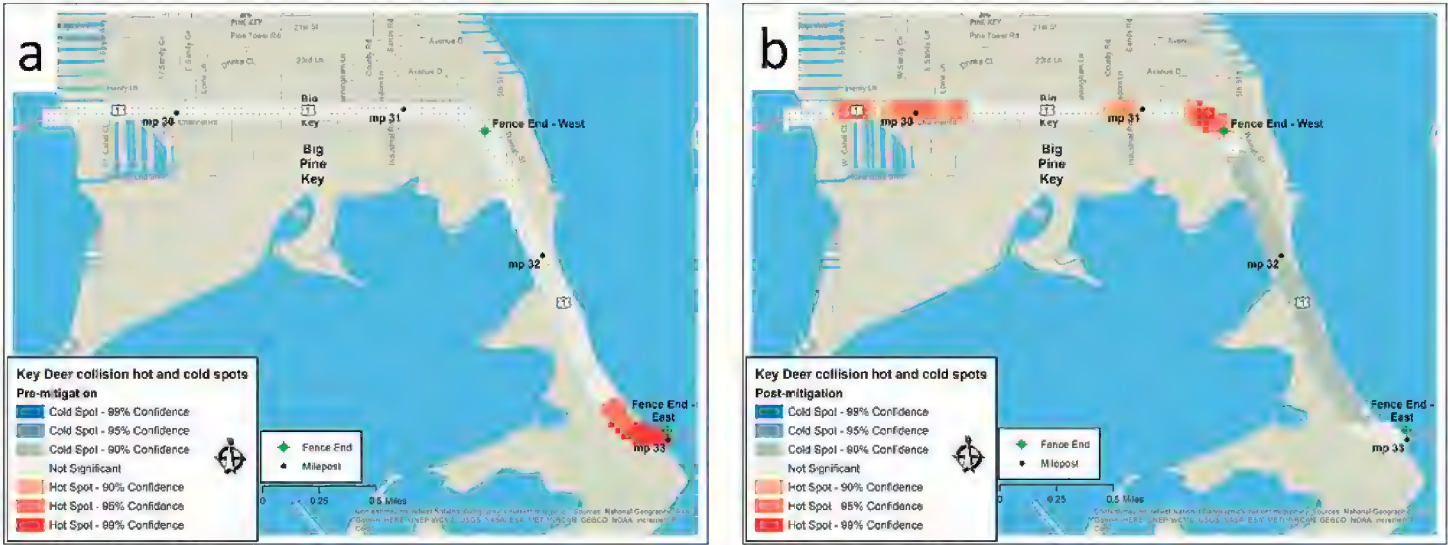


Figure 5. Significant hotspots and cold spots for Key deer-vehicle collisions along US Hwy 1 before (a) and after (b) mitigation. Numbers represent the mile reference posts.

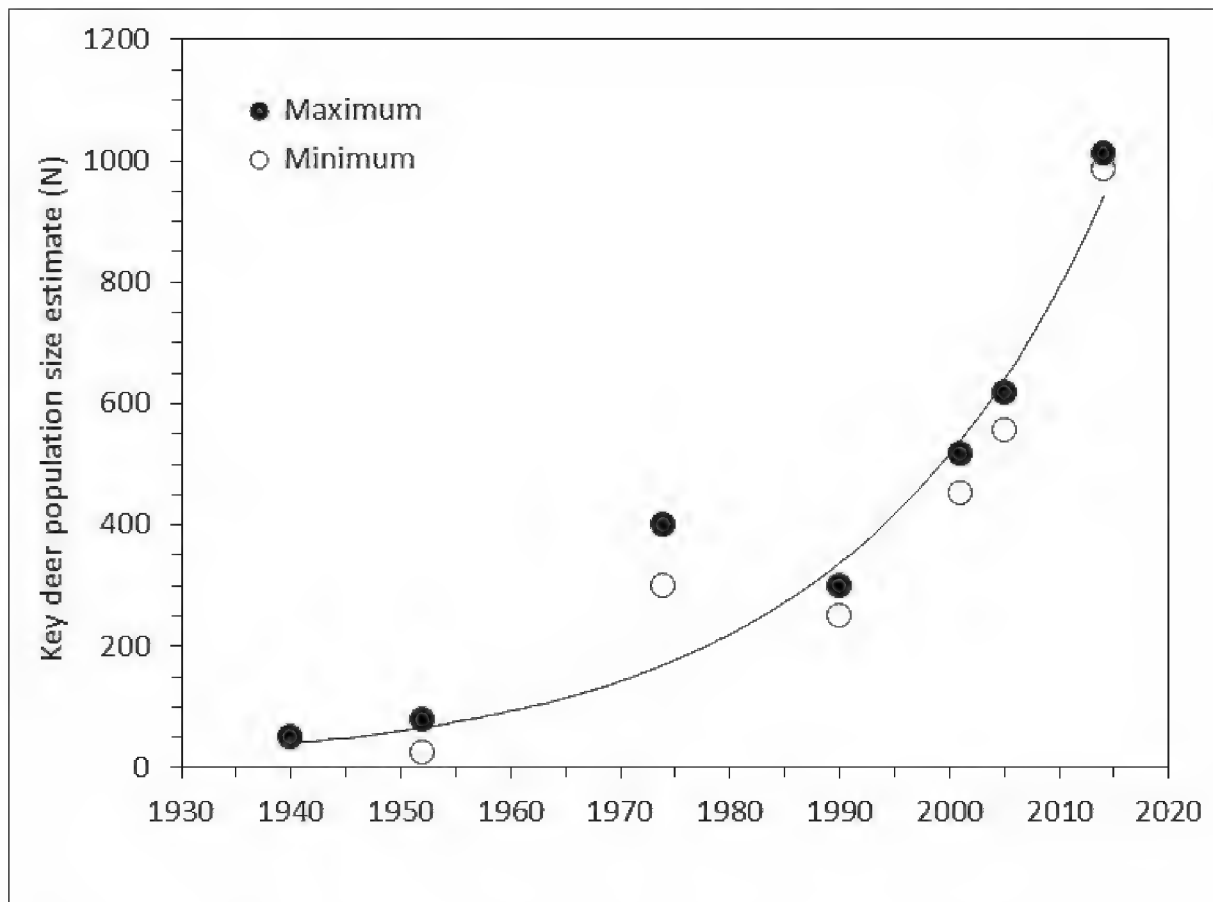


Figure 6. Estimated Key deer population size. An exponential growth curve ($y=e^{(0.04279 \cdot (\text{year})-1853.976)}$; $R^2 = 0.93$) was fitted through data obtained from the literature (see Appendix 1).

The percentage of roadkilled Key deer of the total population size for all roads combined was similar before (average 14.2%, SD=3.2) and after (average 14.9%, SD=1.8) the fence and associated mitigation measures were implemented along the eastern section of US Hwy 1 (Kruskal-Wallis One-Way ANOVA on Ranks, $\text{Chi}^2 = 0.109$, $p = 0.742$) (Fig. 7). The percentage of roadkilled Key deer of the total population size for US Hwy 1 on Big Pine Key was also similar before (7.6%, SD=2.1) and after (7.5%, SD=1.8) mitigation ($\text{Chi}^2 = 0.017$, $p = 0.895$). However, there was a substantial decrease (90.0%) in the mitigated section (before (3.3%, SD=1.2), after (0.3%, SD=0.2)) ($\text{Chi}^2 = 15.652$, $p < 0.001$). At the same time, there was a substantial increase (68%) in the unmitigated section on Big Pine Key (before (4.3%, SD=1.1), after (7.2%, SD=1.7)) ($\text{Chi}^2 = 14.126$, $p < 0.001$). There was still an increase in the unmitigated section (65%) on Big Pine Key when the 90% confidence hotspot at the fence-end was excluded (before (3.5%, SD=0.9), after (5.8%, SD=1.5)) ($\text{Chi}^2 = 12.678$, $p < 0.001$). For the unmitigated highway section west and east of Big Pine Key there was no significant difference before (1.2%, SD=0.6) and after (1.4%, SD=0.6) mitigation ($\text{Chi}^2 = 0.626$, $p = 0.429$).

Traffic volume

In 2017, US Hwy 1 on Big Pine Key had an Annual Average Daily Traffic Volume (AADT) of 18,590–19,600 vehicles per day depending on the location of the traffic counter (FDOT 2018). The vast majority were passenger cars (92.2%) and 7.8% of the vehicles were trucks (single unit, combination trailer, and multi-trailer trucks com-

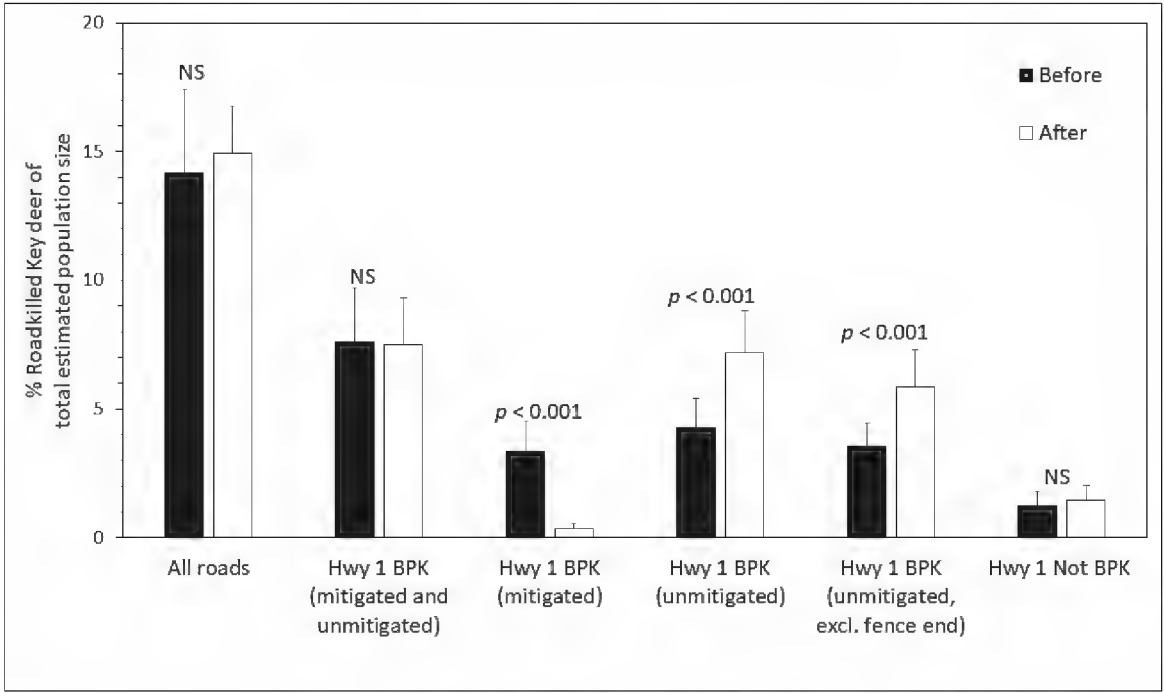


Figure 7. The average percentage (and SD) of roadkilled Key deer of the total estimated population size in the years before and after implementation of the mitigation measures along the eastern section of US Hwy 1 on Big Pine Key (BPK).

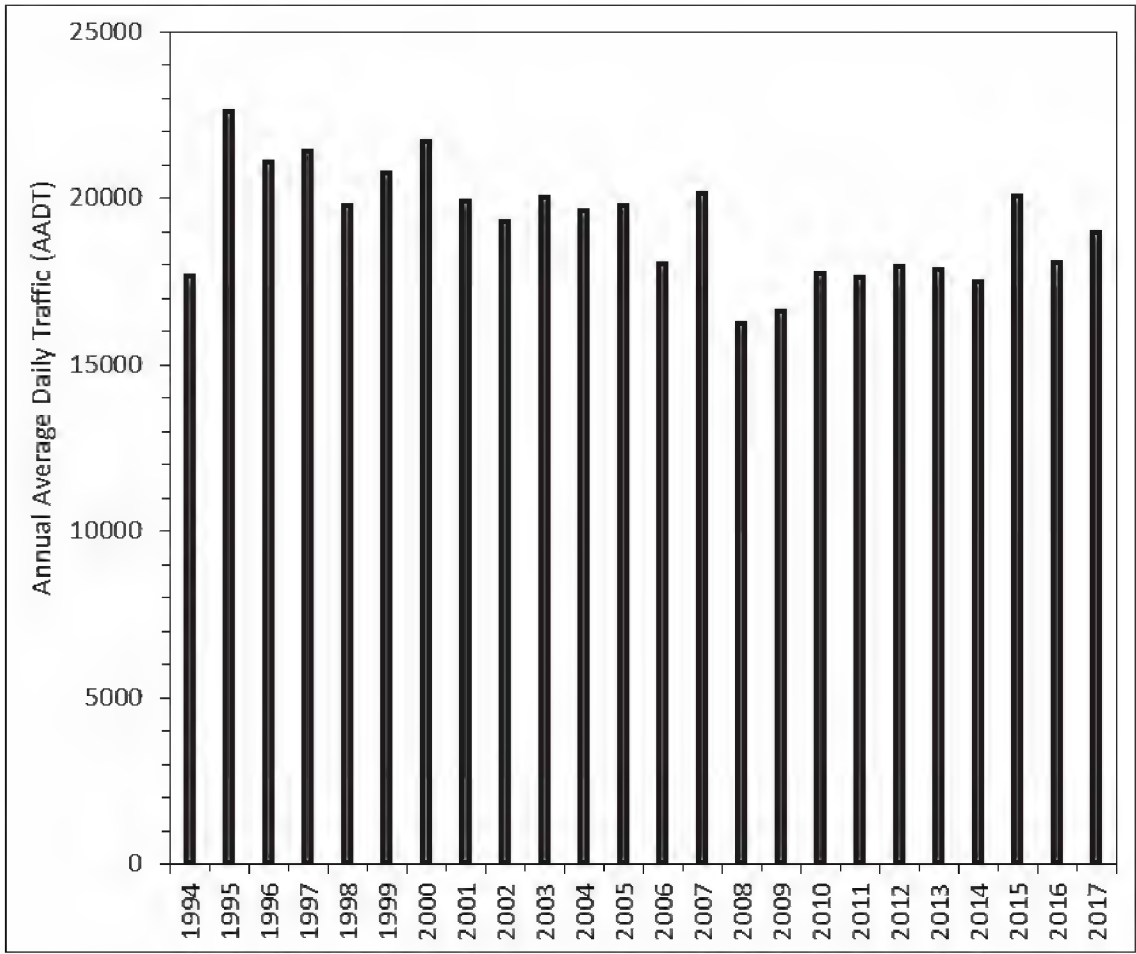


Figure 8. Annual Average Daily Traffic (AADT) on US Hwy 1, Big Pine Key (URS 2017; FDOT 2018).

bined) (FDOT 2018). The average and median AADT before mitigation (1994–2000) was higher (mean = 20,799; median = 21,186; SD = 1,600) than after mitigation (2003–2016) (mean = 18,450; median = 18,053; SD = 1,310) (two-sided t-test $t(19) = -3.6035$, $p = 0.002$) (Fig. 8).

Effectiveness of the mitigation measures

Before the mitigation measures were implemented, the average number of Key deer roadkill per mile per year was 8.4 for the mitigated road section, and 0.4 for the control section (Fig. 9). After the implementation of the mitigation measures, Key deer roadkill decreased by 95.0% in the mitigated road section to 0.5 Key deer roadkilled per mile per year. After the implementation of the mitigation measures Key deer roadkill increased by 112.0% in the control section to 0.8 Key deer roadkilled per mile per year. The BACI effect was 8.8; there were nearly 9 fewer roadkilled Key deer per mile per year in the mitigated road section when corrected for what happened in the control section. In the context of the BACI analysis, the percentage reduction in Key deer-vehicle collisions in the mitigated road section was 94.8%. The interaction of the before-after and control-impact parameters was significant (one-sided ANOVA $F_{1,44}=46.63, p < 0.001$). This meant that the effect of time (before-after) on the number of roadkilled Key deer indeed depended on the implemented mitigation measures.

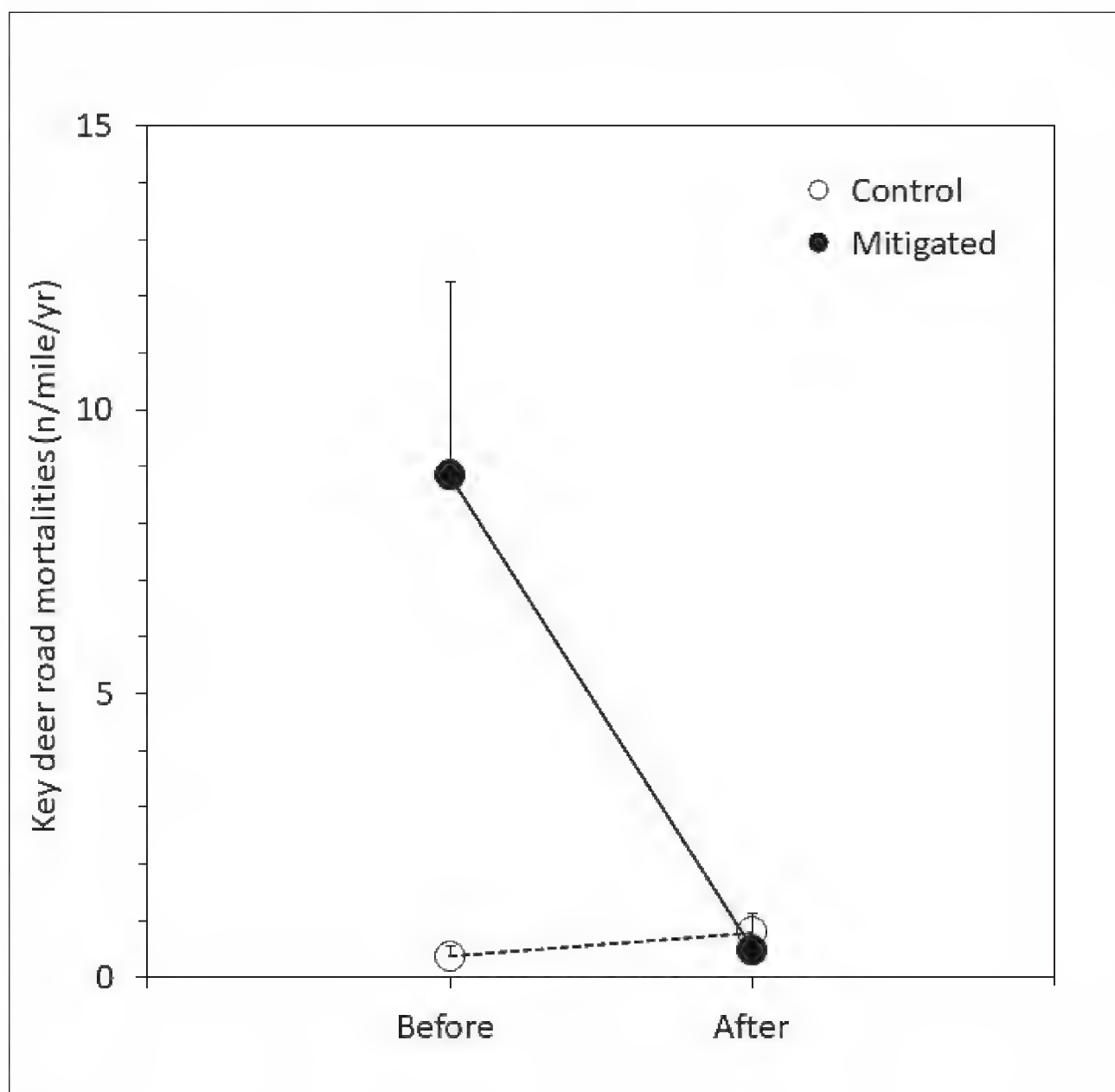


Figure 9. The average number (and SD) of Key deer-vehicle collisions per mile per year in the control and mitigated road section before and after the mitigation measures were implemented.

Discussion

Key deer road mortality and spatial patterns

Direct road mortality has consistently been the most common recorded cause of mortality for Key deer since record keeping began. Therefore, if the objective is to reduce unnatural mortality for Key deer, reducing direct road mortality should be explored first. After the mitigation measures were implemented, Key deer road mortality was concentrated along the unmitigated western section of US Hwy 1 on Big Pine Key. Therefore, this is the road section that should be prioritized if the objective is to reduce direct road mortality of Key deer.

Effectiveness of the mitigation measures

Based on the BACI analysis, the wildlife fence and associated mitigation measures along the eastern section of US Hwy 1 on Big Pine Key were highly effective (94.8%) in reducing Key deer-vehicle collisions along the mitigated road section. However, when corrected for the population size, Key deer road mortality was similar before and after highway mitigation for all roads combined as well as for US Hwy 1 on Big Pine Key (mitigated and unmitigated section combined). Similar to the absolute numbers, the percentage of roadkilled Key deer in relation to the population size sharply decreased by 90.0% in the mitigated section of US Hwy 1 but substantially increased by 68% in the unmitigated section of US Hwy 1 and by 65% when the fence-end effect was excluded. The hypothesis that the continuing increase in Key deer-vehicle collisions after the mitigation measures were implemented may have been associated with an increase in Key deer population size must be rejected. Similarly, traffic volume can also not explain the increase in collisions. Traffic volume was, on average, lower after the implementation of the fence and associated mitigation measures, likely because of the lead-up to the economic crisis in 2008 and the gradual recovery afterwards. However, in general, higher traffic during certain hours of the night is positively correlated with an increase in collisions with Key deer (Braden et al. 2020). Our data suggest that while the mitigation measures reduced collisions substantially in the mitigated road section, the overall Key deer road mortality on US Hwy 1 on Big Pine Key was not reduced. Instead, it was moved from the mitigated section to the unmitigated section of US Hwy 1, especially just beyond the fence-end. After mitigation, a significant hotspot of Key deer-vehicle collisions appeared at the western fence-end of the mitigated section of US Hwy 1, likely as a result of some Key deer following the fence and crossing at-grade in higher than average numbers at the fence-end. This is similar to what has been observed for other species (Clevenger et al. 2001; van der Grift and Seiler 2016; Plante et al. 2019). Other significant Key deer-vehicle collision hotspots after mitigation occurred further west along the unmitigated highway section on Big Pine Key.

The increase in Key deer road mortality along the unmitigated section of US Hwy 1 on Big Pine Key can be seen as a form of environmental leakage as the “extraction” was

moved from a now protected area to a non-protected area rather than reduced (Bode et al. 2015). In other words, there was no “net benefit” of the mitigation if the “net benefit” is defined as the gains made in reducing collisions in the fenced road section minus the adverse impacts caused by this mitigation, including an increase in collisions in the adjacent unmitigated road section (Efroymson et al. 2014).

It is important to bear in mind that the overall number of collisions is just one parameter associated with the presence of the mitigation measures along the eastern section of US Hwy 1. For example, even though the overall number of key-deer vehicle collisions along US Hwy 1 was not reduced after mitigation, the remaining collisions mostly occur along the section where the design speed and surroundings (side roads, entrances to businesses, pedestrians, cyclists) may encourage drivers to have lower operating speed and pay more attention to their surroundings compared to the mitigated section of US Hwy 1 (very few side roads, no buildings adjacent to the highway, wide right-of-way). Thus, there may be a lower likelihood of human injuries and human fatalities when hitting a Key deer in the western section of US Hwy 1. Another benefit of the mitigation measures is that the mitigated section of US Hwy 1 also provides safe crossing opportunities for Key deer through the underpasses (Braden et al. 2008; Parker et al. 2011).

Management implications

While the mitigation measures along the eastern section of US Hwy 1 on Big Pine Key were highly effective in reducing Key deer-vehicle collisions, the data indicate that there was no “net benefit” of the wildlife fence in reducing collisions with Key deer along the entire section of US Hwy 1 on the island (mitigated and unmitigated road section combined). Measures that could be considered for the currently unmitigated western road section on the island include erecting a fence behind the businesses and residential properties that are adjacent to US Hwy 1. This would mean that the “first row” or “first block” of buildings would be included in the fenced road corridor, resulting in unhindered access to these buildings from US Hwy 1. A limited number of gaps in the fence, with wildlife guards, would allow for access to areas beyond the first row or block of buildings. In places where natural habitat remains adjacent to US Hwy 1, fenced corridors leading up to US Hwy 1 may be considered for wildlife, including Key deer. The fenced corridors would lead to underpasses (similar to the ones in the eastern mitigated road section) or at-grade crossing opportunities with wildlife guards or electrified barriers embedded in the travel lanes that encourage Key deer to cross the highway straight and to keep them from wandering off to the sides into the fenced road corridor. This measure can be expected to result in a reduction in Key deer collisions of about 95% (with underpasses, see this article) or 40% (with at-grade crossing opportunities, see Lehnert and Bissonette 1997) along the currently unmitigated section of US Hwy 1. Alternatively, an animal detection system may be considered, especially at the western fence-end. The effectiveness of animal detection systems in reducing collisions with large wild animals is extremely variable (33–97%), presumably due to different detection technologies, different target species, different types of warning and speed

limit reduction signs, and driving culture (see review in Huijser et al. 2015b). Nonetheless, an animal detection system along the full length of the 90% probability hot-spot at the western fence-end would affect 18.7% of the remaining collisions with Key deer along US Hwy 1 on Big Pine Key. The fences with two types of crossing opportunities (underpasses, at-grade crossings) and the animal detection system at the western fence end, can, depending on the road length along which they are implemented and dependent on the spatial distribution of Key deer collisions, all be expected to change the current “no net benefit” to a “net benefit” for reducing collisions with Key deer.

Conclusion

In order to substantially reduce the overall number of deer-vehicle collisions along US Hwy 1 on Big Pine Key, the entire highway section on Big Pine Key would need to be mitigated. However, the section of US Hwy 1 that remains unfenced has many buildings and access roads to businesses and residences. This means that there are many competing interests; implementing mitigation measures that are effective in reducing Key deer-vehicle collisions and that also provide safe crossing opportunities for Key deer and other wildlife species will affect other interests on and along US Hwy 1. This case study also illustrates that while fences and associated mitigation measures can be very effective in reducing collisions in the mitigated road section, wildlife-vehicle collisions in the larger area may not be reduced because the collisions can move to nearby unmitigated road sections, especially just beyond fence-ends. This phenomenon is not an indication that wildlife fences do not reduce wildlife-vehicle collisions. Instead, it is an indication that the fenced road section is too short. Therefore it is important to carefully consider the appropriate spatial scale over which highway mitigation measures are implemented and evaluated.

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Appendix I

Table 1A. Key deer population size estimates.

| Year | Minimum (n) | Maximum (n) | Average (min-max) (n) | Source |
|------|-------------|-------------|-----------------------|-------------------------|
| 1940 | ? | 50 | 50 | Hardin et al. (1984) |
| 1952 | 25 | 80 | 52.5 | Dickson (1955) |
| 1974 | 300 | 400 | 350 | Klimstra et al. (1974) |
| 1990 | 250 | 300 | 275 | Seal and Lacy (1990) |
| 2001 | 453 | 517 | 485 | Lopez (2001) |
| 2005 | 555 | 619 | 587 | Roberts (2005) |
| 2014 | 987 | 1012 | 999.5 | Villanova et al. (2017) |